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POWERFUL SOURCES OF PULSE HIGH-FREQUENCY ELECTROMECHANICAL TRANSDUCERS FOR MEASUREMENT, TESTING AND DIAGNOSTICS

Aim. Development of powerful current radio pulses generators (CRPG) for powering high-frequency electromechanical transducers based on IGBT transistors. **Methodology.** To carry out the research, the statements of the magnetic and electromagnetic fields interaction with electric and ferromagnetic material, electric circuits, structure of radio electronic devices theory were used. **Results.** The main provisions for creating powerful broadband generators for powering electromechanical transducers based on IGBT transistors are determined. It is shown that the generators intended for use in measurements, testing and diagnostics should provide adjustment of the frequency and duration of the output current pulses, and also provide current in the transducer inductor of several hundred amperes. The connection between the power frequency of the resonant electromechanical transducer and the gap between the transducer and the surface of the metal being diagnosed is established. A CRPG variant for powering electromechanical transducers in the frequency range 1 ... 3 MHz and the duration of current pulses of 1 ... 20 periods of the filling frequency is developed and manufactured. The peak current in the inductor of a high-frequency electromechanical transducer has reached 450 A. **Novelty.** For the first time, the possibility of using powerful IGBT transistors in electronic devices working in a key mode in push-pull circuits for feeding high-frequency electromechanical transducers is shown. **Practical value.** Using the results obtained will allow the creation of new instruments for measurement, control and diagnostics with wider characteristics. References 12, figures 6.

Key words: powerful transistors, radio pulse generator, electromagnetic field, conductive and ferromagnetic metal, high-frequency current, inductor.

Цель работы. Разработка основных положений по созданию мощных источников импульсов тока для питания высокочастотных электромеханических преобразователей для измерений, контроля и диагностики электротехнических устройств на базе силовых IGBT транзисторов. **Методика.** Для проведения исследований использовались положения теории взаимодействия магнитных и электромагнитных полей с электропроводным и ферромагнитным материалом, электрических цепей, построения электронных устройств. **Результаты.** Определены основные положения по созданию мощных широкополосных генераторов для питания электромеханических преобразователей на базе силовых IGBT транзисторов. Показано, что генераторы, предназначенные для использования в измерениях, контроле и диагностике, должны обеспечивать регулировку частоты и длительности импульсов выходного тока, а также обеспечивать ток в катушке преобразователя величиной до 450 А. Установлена связь между частотой питания резонансного электромеханического преобразователя и зазором между преобразователем и поверхностью диагностируемого металла. Разработан и изготовлен вариант ИИТ для питания электромеханических преобразователей в диапазоне частот 1...3 МГц и длительности импульсов тока 1...20 периодов частоты заполнения. Пиковая величина тока в катушке высокочастотного электромеханического преобразователя достигла 450 А. **Научная новизна.** Впервые показана возможность применения силовых IGBT транзисторов в электронных устройствах, при ключевом режиме работы в двухтактных схемах для питания высокочастотных электромеханических преобразователей. **Практическая значимость.** Использование полученных результатов позволит создавать новые приборы для измерений, контроля и диагностики с улучшенными характеристиками. Библ. 12, рис. 6.

Ключевые слова: силовые транзисторы, генератор импульсов, электромагнитное поле, электропроводный и ферромагнитный металл, высокочастотный ток, катушка индуктивности.

Introduction. Recently, there has been a growing tendency to use pulse high-frequency electromechanical transducers (PHFEMT) [1-4] for measurement, control and diagnostics of electrically conductive and ferromagnetic metal products. PHFEMT can transform electromagnetic energy into high-frequency mechanical (ultrasonic). This transformation is traditionally called electromagnetic-acoustic (EMA) transformation. The physical nature of EMA transformation can be explained with the help of Fig. 1 (1 – the source of a constant polarization field; 2 – high-frequency inductor; 3 – product; 4 – power lines of a constant magnetic field; 5 – field lines of high-frequency electromagnetic field; 6 – vortex current in the surface skin layer of the product). Conductors with flat inductor current are located in parallel with the conductive or ferromagnetic metal surface (OT – object of testing). The current layer has a linear density $I = I_0 e^{j\omega t}$, which induces a current $I_f = -I_0$ and creates a uniform magnetic field with the amplitude

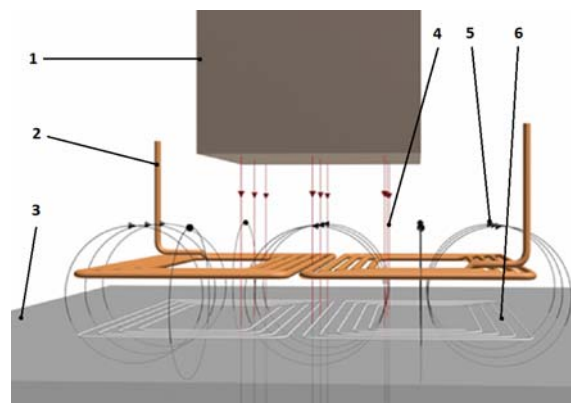


Fig.1 The diagram explains the physical effects of electromagnetic field transformation into high-frequency mechanical (ultrasonic) oscillations

$|H| \propto I_0$, where $j = \sqrt{-1}$, ω – the current frequency in the EMAT inductor. A constant polarization magnetic field

with induction $\vec{B} = \vec{x}_0 B_x + \vec{y}_0 B_y$ is applied to the surface layer of the OT under the inductor. According to [5], alternating stresses are formed in the surface skin layer of the OT, due to the interaction of the magnetic and electromagnetic fields. The total voltage T_{xx} is written in the form

$$|T_{xx}| = |T_{xx}^E + T_{xx}^M + T_{xx}^C| = HB_y \left| 1 - \frac{\mu - 1}{\mu} - j\alpha\beta_t^2 \right|, \quad (1)$$

where T_{xx}^E – the stresses formed due to the electrodynamic effect (Lorentz forces); T_{xx}^M – voltages formed due to magnetic interaction; T_{xx}^C – the stresses formed due to magnetostrictive effects; β_t – generalized parameter that is equal to the ratio of the wave numbers of mechanical and electromagnetic waves $\beta_t^2 = \frac{\bar{\omega}}{c_t^2 \mu_0 \mu \sigma}$;

H – the intensity of the alternating magnetic field; μ_0 – the magnetic constant $4\pi \cdot 10^{-7}$ H/m; μ – the relative magnetic permeability; c_t – the propagation velocity of the high-frequency elastic shear perturbation in the OT material; ω – the frequency of high-frequency elastic mechanical oscillations, which coincides with the frequency of the high-frequency current in the EMA transducer's inductor; α – the magnetostrictive constant; $j = \sqrt{-1}$; σ – electric conductivity of the OT material.

Analysis of the equation (1) shows that the magnitude of the mechanical variable stresses depends on the induction of the polarization magnetic field and the current magnitude in the inductor. When diagnosing ferromagnetic materials, it is very difficult to generate an induction value of the magnetic field in the excitation zone of high-frequency mechanical oscillations of more than 1 T. On the other hand, it is not advisable to significantly increase the induction of the polarization magnetic field, since the EMAT attractive force to the ferromagnetic product will be significant. As a result, it is difficult to scan the OT during diagnostics.

Pulse current in the EMAT inductor can theoretically be increased without special restrictions up to tens of kiloamperes, for example by means of mechanical interrupters. However, it is impossible to use such generators in devices, especially in small ones. In addition, the problem arises when forming high-frequency current pulses in the range from tenths to tens of MHz.

This problem can be solved by increasing the peak power of current pulse sources (CPS) [6-11]. The authors in [6, 7] propose to use powerful short unipolar pulses for powering the PHFEMT, which are not difficult to obtain, for example, with the help of thyristors. However, such pulses have a wide frequency spectrum, which reduces their efficiency at given values of diagnostic frequencies. In articles [8-11], it is proposed to apply a pulse packet of certain duration and with a specified filling frequency to feed PHFEMT. In this case, the output voltage in the device [8] does not exceed 300 V, which is unacceptable. The generator [9] allows obtaining significant pulse currents in the load. However, it is made on high-voltage high-frequency electron tubes GMI-83, which require cumbersome high-voltage power supplies. Such generators consume a lot of electricity. The device is

dangerous for maintenance staff. The power sources given in [10, 11] are more promising, but they do not allow increasing the output power. Therefore, the development of high power CPS is of great interest.

The aim of the paper is to develop the main regulations for the creation of powerful current pulse sources for feeding high-frequency electromechanical transducers for measuring, monitoring and diagnostics of electrical devices based on IGBT transistors.

Research and analysis of the developed results.

Analysis of known literature sources [1-11] allowed formulating requirements for CPS, which should provide EMAT feeding, for example, described in [1-4], in the most constantly used frequency range. It should be formed in EMAT with an input resistance from fractions of up to several Ω current pulse packets with a filling frequency from 1 to 3 MHz. The period's number of the pulse filling frequency should be adjustable in the range 1 ... 20 pcs. The maximum peak amplitude of the current in the transducer conductors should reach several hundred amperes. The repetition frequency of the probing pulses should be regulated in the range from 0.01 to 1 kHz, depending on the OT scanning speed.

The authors based on the analysis of the power electronics elements characteristics came to the conclusion that it is expedient to use powerful IGBT transistors in the output stages. To test this assumption, experimental studies were performed of the capabilities of several modern powerful comparatively high-frequency IGBT transistors at high frequencies. It is determined that they do not allow creating a sinusoidal output signal. At the same time, it is shown that in the claimed frequency range, some IGBT transistor models switch with sufficient time intervals in push-pull circuits.

To implement the developed technical solution, it is proposed to form the CPS output pulse in the form of a meander, and the sinusoidal component allocation is carried out using the EMAT resonant circuit or a separate filter. This approach makes it possible to provide an acceptable thermal operating mode of the transistors, especially at high probing frequencies, and to obtain significant amounts of excited currents in the load. The expediency of using parallel switching up to 5 transistors in each arm of a push-pull circuit allows increasing the current in the transducer or increasing the voltage due to the use of high-frequency broadband transformers. The pre-switches in front of the output stages must be powerful enough to quickly fill the gate of the IGBT transistors of the CPS output stage. To quickly switch off the output transistors, the resistance of the pre-output transistors in the open state should be minimal.

The expediency of manufacturing CPS in the form of two main blocks – a signal generator with adjustable parameters and a high-frequency broadband power amplifier is specified.

On the basis of this approach CPS has been developed, which allows fulfilling the requirements necessary for feeding EMAT with modern monitoring, measuring and diagnostic tools. As an example of such a development Fig. 2 shows the electrical circuit diagram of a high-power high-frequency broadband generator.

The signal generator with adjustable parameters is made on a microprocessor U4 of the AT90S1200 type.

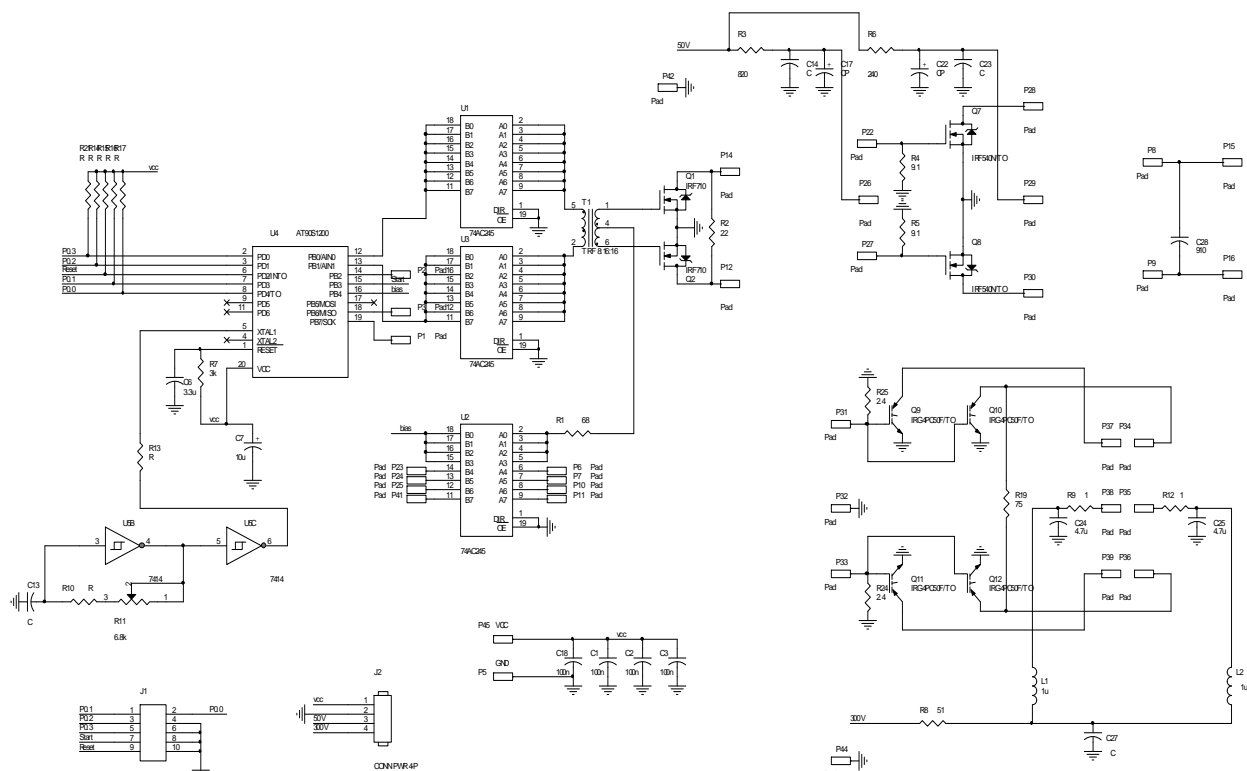


Fig. 2. Electric schematic diagram of CPS for feeding high-frequency electromechanical transducers

It forms two sequences of rectangular pulses IN1 and IN2 with an amplitude of 5V with a pulse ratio of 2 (meander) and the phase opposites that are required to power the subsequent CPS stages. The frequency, pulse ration and the number of pulses are controlled by the buttons PQ0-PQ3 and Reset. Each of the two signals from the microprocessor's output goes to the inputs of the buffered repeaters U1 and U3, executed on the chips of 74AC245 type. Buffered repeaters are used to amplify the current output signal, to provide steep edges, form rectangular pulse sequences IN1 and IN2, and to protect the microprocessor in case of short circuits in the amplifier circuit. To increase the output current, 8 inputs and 8 outputs of each buffered repeater are connected in parallel. The time diagrams of the output signals generators are shown in Fig. 3, where: T1 – the sequence period of rectangular pulses; T2 – total duration of the pulse packet; T3 – the interval period of pulse packet; T4 – the duration of the bias pulse.

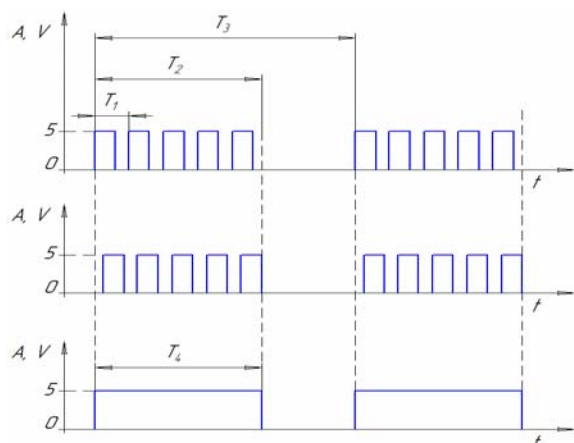


Fig. 3. Time diagram of the output signals generators

The outputs of the buffered repeaters U1 and U3 are loaded on the input winding of the high-frequency wideband transformer T1. From the transformer output T1, rectangular pulses in antiphase go to the transistors gates Q1 and Q2, switched on in a push-pull circuit. Switching on transistors at the same time ensures the sequential opening of only one of them and closing of the other one. Simultaneously, a bias pulse is applied to the middle point of the output winding of the transformer T1. It comes from the microprocessor U4 through the buffer U2 (74AC245), providing a rapid opening of the transistors Q1 and Q2 and their subsequent closing after ending the pulse packet. The duration of the bias pulse T4 is equal to the duration of the T2 packet.

From the outputs of transistors Q1 and Q2, square wave pulses of the packet signal are fed to the input of a high-frequency broadband transformer similar to T1 (not shown in the diagram). Rectangular pulses from the output of the second transformer go to the transistors gates Q7 and Q8 (IRF540N), also included in the push-pull circuit. The stage on transistors Q7 and Q8 serves to amplify rectangular pulses in voltage and current sufficient for the key output stage operation on IGBT transistors Q9 and Q10, Q11 and Q12 (IRG4PC50F), included in pairs in each arm of the push-pull circuit. Parallel switching on two IGBT transistors in each arm allowed increasing the limiting switching current and reducing losses by lowering the resistance of the arm in the open state. The output stage is connected to the previous one using a broadband high-frequency transformer similar to T1 (not shown in the diagram). The output stage is also loaded on a broadband high-frequency transformer (not shown in the diagram), which output is connected to the EMAT, for example [1].

Power units of the generator's stages are not shown in the diagram. To test the developed CPS characteristics, tests were performed when it was connected to the active load and when the EMAT load was operating in a resonance mode.

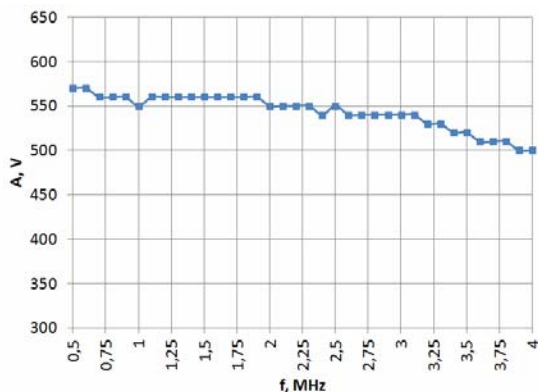


Fig. 4. Amplitude-frequency response of CPS with an active load equal to 0.5Ω

Fig. 4 shows the amplitude-frequency response of CPS with an active load equal to 0.5Ω in the frequency range exceeding the range of 1 ... 3 MHz. The measurements were performed using an oscilloscope SDS7202.

Data analysis (Fig. 4) shows that the amplitude-frequency response of CPS in the frequency range 1 ... 3 MHz is close to uniform. This means that the use of IGBT transistors in the switching mode in the output push-pull stages allows covering the traditionally used frequency range for measurements, monitoring and diagnostics. In this case, the peak current in the active load exceeds 100 A.

Studying generator's operation when connecting resonant EMAT, the following procedure was used. The high-frequency electromechanical transducer [1] was mounted on a metal (high-carbon steel) with various gaps between the inductor and the metal. The CPS frequency controller fed EMAT into resonance. It is taken into account that the basis of any EMAT is a high-frequency inductor and that the inductance of this inductor is different for different gaps. Consequently, the resonant frequency of the transducer will also be different. This position was confirmed by the data in Fig. 5, which showed the amplitude-frequency response of CPS together with EMAT resonant type. In this case, the high-frequency inductor was connected in parallel with an additional capacitor of 10^4 pF. The inductance of the high-frequency inductor, taking into account power cables and CPS output parameters, was about 1 ... 2 μ H. The backlash was established with the help of gaskets made of glass-textile of various thicknesses. The measurements were performed using an oscilloscope SDS7202.

Data analysis (Fig. 5) shows that when the gap is reduced, the EMAT resonance frequency increases approximately in inverse proportion to the frequency of the power current: with a gap of 7 mm – about 1.3 MHz; with a gap of 4.5 mm – about 1.6 MHz; with a gap of 2 mm – about 2.05 MHz and with a gap of 1 mm – about 2.45 MHz. These data confirm that CPS must necessarily have a frequency regulation of the power current. Its own amplitude-frequency response should be close to linear in order to ensure the same power conditions for the

transducer. Especially these requirements are important for automatic or automated measurements, monitoring and diagnostics, when it is impossible to maintain the exact gap size (usually several millimeters).

It is obvious that the CPS current feeding the EMAT can not instantaneously bring into operation the parallel resonant circuit of the electromechanical transducer. This requires several periods of the generator current frequency, Fig. 6. At the same time, the required number of periods for EMAT output to the operating mode also depends on the gap size. Consequently, it is necessary to regulate the periods number of the filling frequency for the pulse packet of the CRPG.

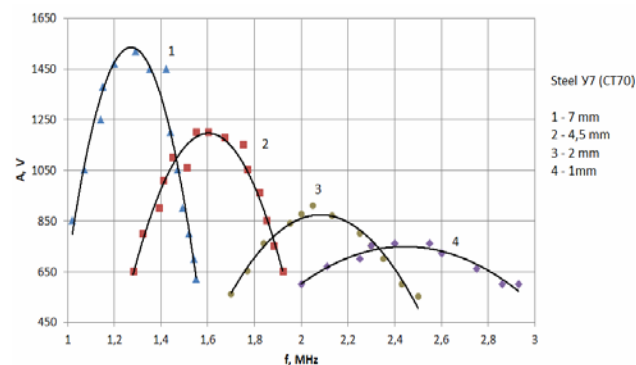


Fig. 5. The amplitude-frequency response of a high-frequency resonant electromechanical transducer [10] connected to CPS at distances (gaps) between a high-frequency conductor and an electrically conductive ferromagnetic OT surface: 1 – 7 mm; 2 – 4.5 mm; 3 – 2 mm; 4 – 1 mm

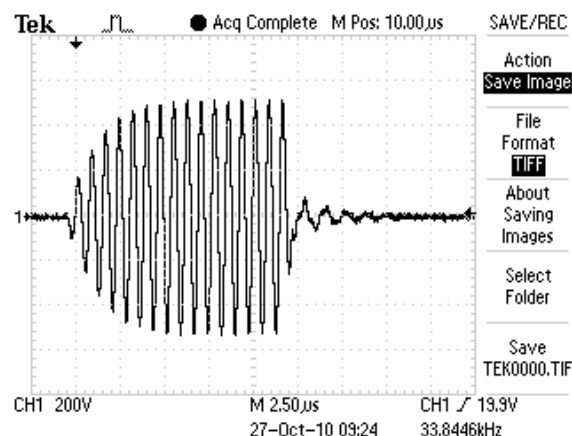


Fig. 6. A typical voltage on the EMAT [1] when feeding CPS

It is known that the current in the resonant circuit exceeds the current coming from the power source [12]. To evaluate its value, a shunt with a resistance of 0.01Ω was built into the parallel resonant EMAT circuit. During resonance, its voltage was 4.5 V. Consequently, the current in the EMAT high-frequency conductor was about 450 A. The requirement to increase the degree of electromagnetic energy transformation into high-frequency mechanical one by increasing the current in the EMAT inductor developed by CPS on the basis of IGBT transistors is satisfied.

Conclusions.

1. The main regulations for the creation of powerful current pulse sources for feeding high-frequency electromechanical transducers for measuring, monitoring and diagnostics of electrical devices based on IGBT transistors are developed.

2. A practical implementation of a powerful current pulse generator based on IGBT transistors of the IRG4PC50F type is proposed, which provides currents of up to 450 A in the frequency range 1 ... 3 MHz with a pulse packet duration of 1 ... 20 in the inductor of a high-frequency electromechanical transducer.

3. It is shown that CPS provides a significant increase in the current of a high-frequency inductor when feeding the resonant EMA transducers, thereby increasing electromagnetic energy transformation into high-frequency mechanical one in electrically conductive and ferromagnetic materials.

4. The necessity to regulate the frequency and duration of power pulses for high-frequency electromechanical transducers intended for measurements, monitoring and diagnostics is determined and experimentally confirmed.

5. It is experimentally determined that the gap increase between the high-frequency EMAT inductor and the surface of an electrically conductive ferromagnetic metal leads to a decrease in the resonant frequency of the transducer, approximately in inverse proportion to the current frequency. This effect is due to the influence of metal properties on the inductance of the high-frequency EMAT inductor located with a gap above the product surface.

REFERENCES

1. Miguschenko R.P., Suchkov G.M., Radev H.K., Petrishchev O.N., Desyatnichenko A.V. Electromagnetic acoustic transducer for ultrasonic thickness gauging of ferromagnetic metal items without removing dielectric coating. *Technical electrodynamics*, 2016, no.2, pp. 78-82. (Rus).
2. Suchkov G.M., Taranenko Yu.K., Khomyak Yu.V. A non-contact multifunctional ultrasonic transducer for measurements and non-destructive testing. *Measurement Techniques*, 2016, vol.59, no.9, pp. 990-993. doi: **10.1007/s11018-016-1081-3**.
3. Boughedda H., Hacib T., Chelabi M., Acikgoz H., Le Bihan Y. Electromagnetic acoustic transducer for cracks detection in conductive material. *2015 4th International Conference on Electrical Engineering (ICEE)*, Dec. 2015, pp. 1-4, doi: **10.1109/INTEE.2015.7416717**.
4. Li B. Application of electromagnetic acoustic in steel pipe inspection. *2016 35th Chinese Control Conference (CCC)*, Jul. 2016, pp. 9539-9542. doi: **10.1109/ChiCC.2016.7554872**.
5. Ermolov I.N. *Teoriya i praktika ultrazvukovogo kontrolya* [Theory and practice of ultrasonic testing]. Moscow, Mashinostroenie Publ., 1981. 240 p. (Rus).
6. Zhukov V.K., Ol'shanskii V.P. Electromagnetic-acoustic equipment UVT-01N for inspecting the wall thickness of drilling pipes. *The Soviet journal of nondestructive testing*, 1986, vol.22, iss.2, pp. 76-80.
7. Bolyukh V.F., Oleksenko S.V., Shchukin I.S. Comparative analysis of linear pulse electromechanical converters electromagnetic and induction types. *Technical electrodynamics*, 2016, no.5, pp. 46-48. (Rus).
8. Viskushenko A.A., Remnev A.M., Smerdov V.Yu. *A High-Voltage Pulse-Packet Shaper. Instruments and Experimental Techniques*, 2001, vol.44, iss.1, pp. 58-60. doi: **10.1023/A:1004128932683**.
9. Pachkovskii L.S., Nevolin O.V. High-power broadband radio-frequency pulse generator to excite ultrasonic vibrations by the contactless electromagnetic-acoustic method. *Sov. J. Nondestr. Test.*, 1977, vol.13, iss.6, pp. 704-706.
10. Suchkov G.M., Petrishchev O.N., Cherednichenko I.V., Fedorov V.V., Desyatnichenko A.V., Khashchina S.V., Maslova M.S. A generator of probing pulses for EMA flaw detectors. *Russian Journal of Nondestructive Testing*, 2012, vol.48, no.9, pp. 537-540. doi: **10.1134/s1061830912090082**.
11. Miguschenko R.P., Suchkov G.M., Taranenko Yu.K., Petrishchev O.N., Desyatnichenko A.V. Generators of current sounding impulses for supplying electromagnetic acoustic transducers. *Quality Control Tools and Techniques*, 2015, no.2(35), pp. 5-11. (Rus).
12. Aseev B.P. *Osnovy radiotekhniki* [Foundations of radiotechnics]. Moscow, Svyazizdat Publ., 1947. 572 p. (Rus).

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